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APPLYING THE DESIGN OF EXPERIMENTS TO MODEL THE ENERGY CONSUMPTION OF TYPICAL SINGLE-FAMILY HOUSE IN BOSNIA AND HERZEGOVINA

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Abstract

The building sector in Bosnia and Herzegovina is a major energy consumer due to the age, inadequate maintenance, and poor energy characteristics of the majority of buildings. More than 90% of the residential buildings are categorized as individual, single-family houses, accounting for more than 80% of energy consumption. It is of great importance to model the impact of architectural, construction elements, and other relevant parameters on the building's energy consumption. Using the statistical method of design of experiments, a mathematical model is developed a model for the annual energy consumption of a typical residential building based on the building's relevant parameters. The model considers climatic conditions, architectural and construction features, and the characteristics of the installed heating system. This model enables identification of key factors influencing energy consumption and a rapid evaluation of potential energy savings through the implementation of energy efficiency measures. The model is developed for a typical building from the Typology of Residential Buildings of Bosnia and Herzegovina, specifically in the category of single-family houses constructed between 1981 and 1990, representing more than 200000 buildings. The validation of the model demonstrated its effectiveness in predicting the energy consumption of a representative building, therefore the analysis results can be extrapolated to all buildings within the same category.

Keywords: residential sector; design of experiments (DOE); full factorial design (FFD); energy consumption; energy efficiency

1. Introduction

The building sector has the largest share in energy consumption and global greenhouse gas emissions. In the European Union, energy production and consumption account for 75% of greenhouse gas emissions, with approximately 40% attributed to the building sector. In 2021, Bosnia and Herzegovina (B&H) consumed 48,73 GWh of final energy, with the building sector being the largest consumer, followed by transport and industry [1], as shown in Figure 1. Within the residential sector of B&H, 72% of total energy consumed is used for heating.

The building stock and thermo-technical systems in B&H exhibit energy characteristics that offer significant energy-saving potential, through the implementation of energy efficiency measures. By examining the Typology of residential buildings in the country, where buildings are categorized by construction period and architectural-constructional characteristics, it is possible to gain insights into the prevalence of specific building types and their energy performance [2]. According to the Typology of Residential Buildings in B&H, 93,11% of residential buildings in B&H are single-family houses, while high-rise buildings are the least represented with 0,3%. Numerous studies focused on reducing energy consumption in B&H building stock [3], [4], and the benefits of improving thermo-technical systems [5], [6], due to the poor energy characteristics of buildings, low efficiency of typical systems, and the considerable potential for reduction of energy consumption.

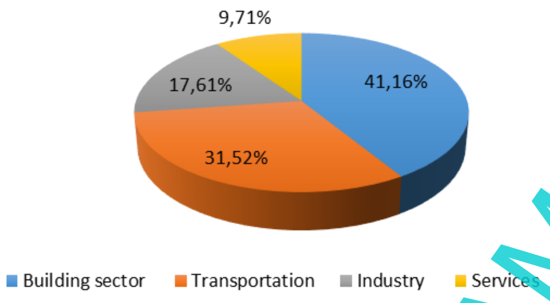


Fig. 1. Distribution of final energy consumption across various sectors in B&H, 2021[1]

Energy performance of buildings is influenced by various factors, including climatic conditions, architectural and construction characteristics, devices utilized, their usage time, and occupancy patterns. Zahraee et al. (2014.) investigated methods for enhancing energy savings in residential buildings by examining three climate factors: temperature, humidity, and airflow. The research employs building simulation and Design of Experiment (DOE) techniques to evaluate the impact of these factors on energy savings and cooling load. Results have shown that temperature and humidity have the most significant influence on energy savings, where optimal values of factors are determined to achieve the highest energy savings within the model's range [7]. Calculation methods and software adhering to relevant standards are frequently employed to examine the impact of energy efficiency measures on residential buildings. Shabunko et al. (2018) presented the results of an analysis of electricity consumption for over 400 residential buildings in Brunei Darussalam using EnergyPlus [8]. The models showed that the specific annual energy consumption of this type of buildings is around 64,2 to 47,8 kWh/m^{2}annual, where HVAC systems have the largest share in electricity consumption. This research highlights the effectiveness of engineering models in establishing benchmarks and simulating conditions for enhancing energy performance in buildings. Garcia-Cuadrado et al. (2022) utilized the Response Surface Method (RSM) to develop a model for calculating energy consumption for heating and cooling in single-family homes across three different climate regions [9]. Their research involved varying set temperature for heating and cooling and altering heat transfer coefficients of external walls by changing thermal insulation thickness. Energy simulation results from DesignBuilder are compared with estimates from the simplified model derived from the RSM analysis. The results showed a deviation of less than 3% between the two methods, demonstrating that the mathematical prediction models are suitable for studying the energy performance of buildings while saving computational time, costs, and associated human resources. In a study presented in Pekdogan et al. (2020), thermal performance of external walls is examined employing a three-level full factorial statistical experimental design. The research focused on an opaque wall in low-energy buildings to analyse the impact of various factors, such as location (A), orientation (B), insulation location at the wall cross section (C), and month of the year (D), on heat loss or gain. The study encompassed different climatic regions of Turkey (Erzurum, Ankara, and Izmir) with conducted 81 experiments. The resulting Analysis of Variance (ANOVA) table indicated that the month of the year, location, and orientation are significant factors for heat transfer through brick walls. Additionally, the interaction effects of factors AB, AD, BD and CD is shown to be significant [10].

The main objective of this study is to develop a mathematical model for analysing the energy characteristics of a representative residential building for quick assessment of its energy consumption and energy-saving potential. A full factorial design is employed to evaluate the impact of selected factors on energy consumption for heating. The analysis is based on dynamic simulation of energy characteristics for a representative single-family house, constructed in the period between 1981 and 1990, whereby this category includes approximately 28% of the total number of buildings in the building sector of B&H.

2. Methodology

2.1. Representative building from the Typology of residential buildings in Bosnia and Herzegovina

In the "Typology of Residential Buildings in Bosnia and Herzegovina," residential buildings are categorized into six distinct construction periods and four different building types, as shown in Figure 2 [2]. Representative buildings are statistically selected for each category, serving as typical examples of their respective categories based on their architectural characteristics. More than 90% of the residential buildings are categorized as individual, single-family houses (SFH), accounting for more than 80% of energy consumption. The focus of the presented analysis is on SFH category, constructed during the period from 1981 to 1990. This category comprises 236075 buildings, which is approximately 28% of the total number of buildings in the B&H residential sector.

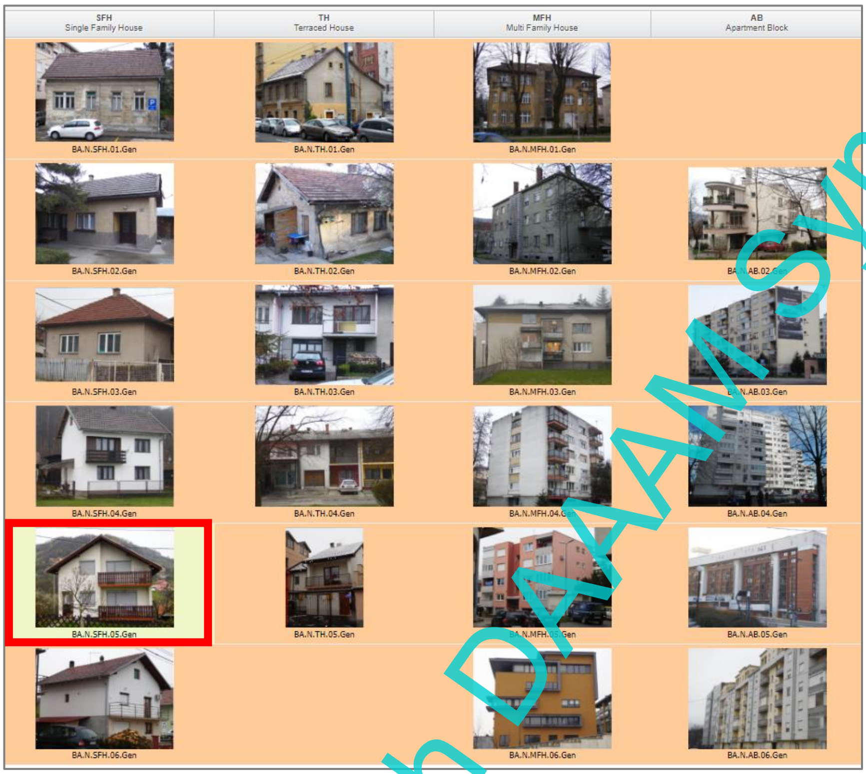


Fig. 2. Classification of residential buildings according to the "Typology of residential buildings in Bosnia and Herzegovina" [11]

The energy characteristics of the representative building, marked with red in Figure 2, are examined in this study. The representative building has two floors. There is a garage in the basement and an impassable attic above first floor ceiling, both of which are treated as unheated areas. The building's envelope consists of hollow brick blocks with 5 cm of thermal insulation, wooden windows with double glazing, and wooden exterior doors. The roof is a two-sided wooden structure with clay roof tiles. The interior is divided by inner walls into separate rooms, each representing a distinct thermal zone. The corridors on both floors are connected by an internal staircase and treated as a single thermal zone. To analyse the energy performance of a building, the study used an designed internal temperature of 20°C for the living room, kitchen, and bedrooms, and 24°C for the bathrooms, as specified by the BAS EN 12831 standard. Table 1 provides basic information about the building's geometry, such as gross area of the base, the net heated surface, and the building compactness ratio. The heat transfer coefficients of characteristic construction elements are shown in Table 2.

Number of floors	2
The gross area of the base of the building	69,66 m^2
Net area of the heated space	101,44 m^2
The volume of the heated space	250,15 m^3
Building compactness ratio	0,83

Table 1. Basic data on building geometry

Heat transfer coefficient [W/m^{2}K]	Outer wall 1	Outer wall 2	Ceiling 1	Ceiling 2	Ceiling 3	Roof	Floor	Window	Outer door
	0,499	0,643	0,433	1,564	0,344	0,615	0,531	2,90	2,9

Table 2. Heat transfer coefficient for particular construction elements

2.2. Modelling the energy performance of a representative building

Building energy performance is modelled using DesignBuilder software, which incorporates EnergyPlus simulation tool. The study analyse how energy consumption for heating varies based on values of selected factors: the wall heat transfer coefficient (U_{wall}), heat transfer coefficient of the ceiling to the unheated attic (U_{ceiling}), the solar heat gain coefficient (*SHGC*), and the heating system efficiency (η_{H}). Simulations are conducted according to a design matrix, and the mathematical relationship is established using the Minitab software version 19. Figures 3 and 4 display a visual representation of the selected single-family home (SFH) constructed between 1981 and 1990, as well as the graphical interface of the model in DesignBuilder.

Fig. 3. The visual representation of the selected representative building object from TABULA registry SFH 1981–1990 [2]

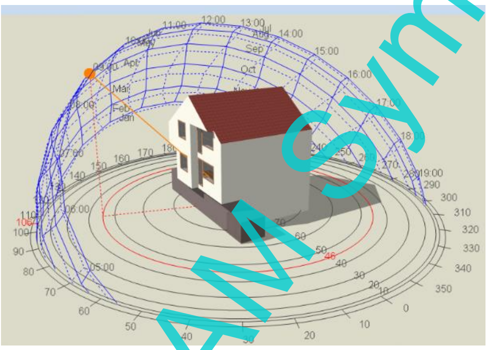


Fig. 4. Graphical interface of the representative object SFH 1981–1990 as designed in DesignBuilder.

EnergyPlus employs hourly data to define external conditions when simulating the energy performance of buildings. National Meteorological Service-monitored data, such as air temperature, atmospheric conditions, solar radiation, wind speed, and direction, are incorporated into the analysis [12]. The SFH examined in this study is located in Banja Luka, B&H, north climate region known for its warm summers, cold and snowy winters, and partial cloudiness throughout the year. Figures 5 and 6 display the average monthly values of the highest and lowest daily temperatures and the average daily short-wave solar energy reaching the ground. Air temperatures fluctuate between -3°C and 28°C annually, seldom dropping below -10°C or exceeding 33°C. July is the hottest month, with an average highest daily temperature of 27°C, while January is the coldest month, with an average lowest daily temperature of -3°C [13].

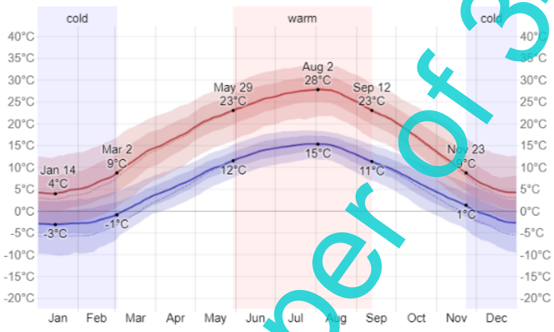


Fig. 5. Average daily external air temperatures

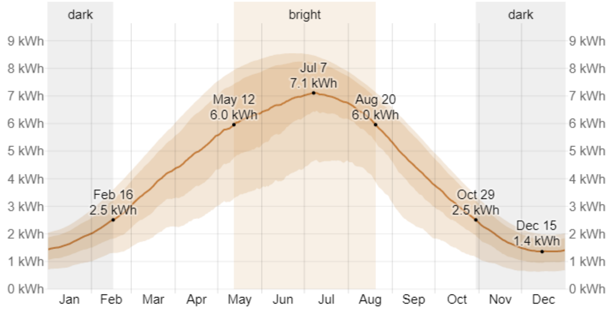


Fig. 6. Average daily shortwave solar energy reaching the ground

For the purpose of the analysis, it is assumed that a family of four lives in the house, with two working adults and two children. This assumption helped establish the occupancy schedule for a week, taking into account that weekdays and weekends have different occupancy rate. As shown in Figure 7, two separate schedules are created for weekdays and weekends. For a typical family of four, most members are absent from the house on weekdays between 07:00 and 17:00, and it is assumed that all members are present from 22:00 to 07:00 during the night period.

The occupancy of the residential unit, or the time spent by people in the building, influences the usage of lighting, electrical appliances, and other household devices, thereby affecting the intensity of internal heat gains. In analysing the internal heat gains of this SFH, factors such as the operation time of the electrical water heater, household appliances, various electrical devices, and lighting are considered. A specific installed lighting power of 5 W/m^2 is used for calculating the internal heat gains.

The typical building is equipped with individual solid fuel stoves (wood and coal), with the efficiency of 50% [2], indicating substantial energy losses in such systems. In the DesignBuilder software, a heating system schedule is developed, as shown in Figure 8. The schedule is set according the assumption that the heating system operates at full capacity from 06:00 to 22:00, seven days a week. The heating system's operation is governed by the internal temperature, meaning it will continue to function until the room temperature reaches the preset internal temperature value.

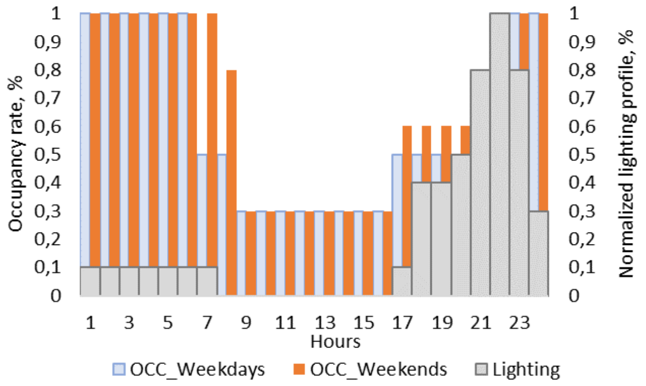


Fig. 7. Occupancy rate and lighting hourly profile

```
For: Weekdays SummerDesignDay,
Until: 06:00, 0,
Until: 22:00, 1,
Until: 24:00, 0,
For: WinterDesignDay,
Until: 24:00, 1,
For: Weekends,
Until: 06:00, 0,
Until: 22:00, 1,
Until: 24:00, 0,
For: Holidays,
Until: 06:00, 0,
Until: 22:00, 1,
Until: 24:00, 0,
For: AllOtherDays,
Until: 24:00, 0;
```

Fig. 8. Heating system operation schedule modelled in DesignBuilder

2.3. Research method

Design of experiments (DOE) is a statistical method employed to plan and analyse experiments results, as well as to interpret the results obtained either experimentally or through simulations. To understand the effect of multiple factors and their interactions on a system or process's response, experiments must be systematically conducted using factorial designs, where several factors are altered during each experimental run. Factorial designs can be executed in two ways: full factorial design (FFD), which analyses all possible factor combinations, and fractional factorial design, which examines only a portion of the possible combinations [14].

In this study, the FFD is employed for statistical analysis to examine the impact of specific factors on the response, which in this case is the energy consumption for heating. The analysis considered four factors, each on two levels. Following factors are considered: the wall heat transfer coefficient (U_{wall}), heat transfer coefficient of the ceiling to the unheated attic ($U_{ceiling}$), the solar heat gain coefficient (SHGC), and the heating system efficiency (η_H). The low and high levels of each factor are determined based on data from the Typology of Residential Buildings in B&H. The low level (-1) represents the poorest energy characteristics found in this category of buildings, while the high level (+1) represents the best energy performance. The values for the (+1) level are complied with the Rulebook on Minimum Requirements for Energy Characteristics of Buildings [15]. The wall heat transfer coefficient is calculated by varying the thickness of the external walls' thermal insulation, with the (-1) level referring to a wall without insulation and the (+1) level referring to a wall with 20 cm of insulation. A similar procedure is applied to determine the ceiling heat transfer coefficient factor level. The building currently has double-glazed windows with wooden frames, but according to the Typology of Residential Buildings in B&H, 26,2% of buildings in this category have single-glazed windows. Therefore, the SHGC factor value at the (-1) level is characteristic of wooden windows with single glazing [2], while the value at the (+1) level is characteristic of PVC windows with triple glazing. The heating system efficiency factor value at the (-1) level represents the efficiency of solid fuel stoves typically installed in the building, while the value at the (+1) level represents the efficiency of a newly installed central heating system with pellet boiler. Factors considered in this study and their levels are shown in Table 3.

Factor	**Level**	
	-1	1
U_{wall}	1,454	0,18
SHGC	0,858	0,242
$U_{ceiling}$	2,046	0,178
η_H	0,5	0,9

Table 3. Considered factors and their levels

In this study, a 2^4 factorial design is employed. The experimental matrix contains 16 simulations, where each simulation run represents specific combination of factor levels and corresponding energy consumption for heating.

3. Results and discussion

Upon establishing the required input parameters, the building's energy characteristics are calculated using DesignBuilder software. Following, the FFD, is employed to analyse the impact of selected factors on the building energy consumption for heating.

3.1. Energy performance of a representative building

Using DesignBuilder, energy characteristics are calculated by considering various factors such as the local climate data, building orientation, occupancy, energy consumption of electrical devices and lighting, and their typical usage periods. Table 4 provides a breakdown of heat losses through individual building elements, and shows that the total heat losses are 9,22 kW. The largest heat losses occur due to infiltration through joints and gaps, followed by losses through glazing and external walls.

Heat losses		
Heat losses through glazed surfaces	2,33 kW	24,01 W/m^2
Heat losses through external walls	2,27 kW	23,41 W/ m^2
Heat losses through the ceiling	0,48 kW	4,96 W/ m^2
Heat losses through the roof	0,39 kW	4,01 W/ m^2
Heat losses through the floor towards the unheated basement	0,14 kW	1,43 W/ m^2
Heat losses to the ground	0,43 kW	4,47 W/ m^2
Heat losses due to infiltration	3,18 kW	32,73 W/ m^2
Total heat losses	9,22 kW	95,02 W/ m^2

Table 4. Building heat load

A simulation of energy consumption in the analysed residential building is conducted, considering factors such as the building's heat losses, the heating system operating time, and the effects of occupancy, lighting, and various electrical appliances. The daily energy consumption patterns, temperatures, and heat balance for a heating season are shown in Figure 9.

Fig. 9. Daily diagrams of energy consumption, temperature and heat balance

From Figure 9, it is visible that the dominant building energy consumption is for heating. The peak energy consumption occurs on December 13, reaching 125,25 kWh. The energy consumption pattern corresponds with external temperature fluctuations. The heat balance diagram demonstrates that heat losses through the building's envelope are counterbalanced by the heat gains from lighting, electrical devices, occupants, and solar gains and heating system, as well. For a more comprehensive analysis, Figure 10 presents a half-hourly energy consumption and temperature chart for the coldest month in Banja Luka region.

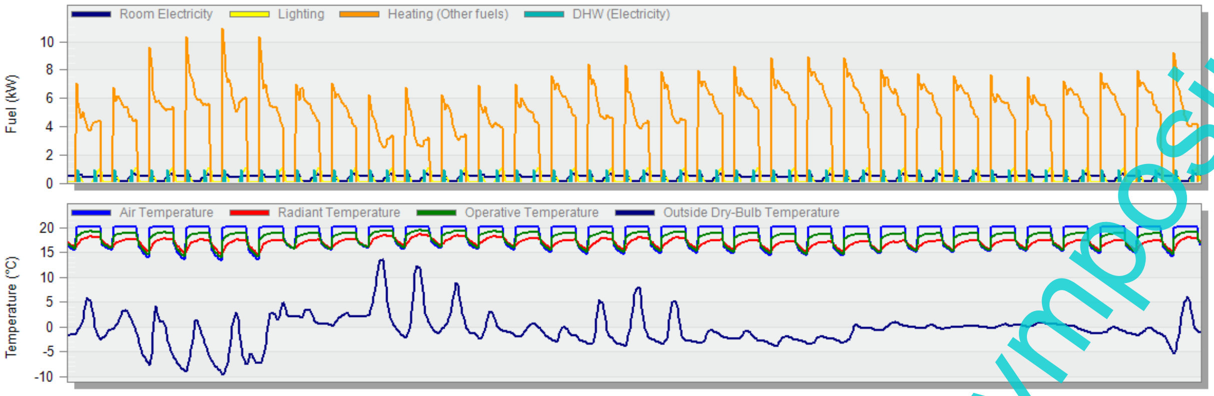


Fig. 10. Half-hourly diagram of energy consumption and temperatures for the month of January

In Figure 10, the operating parameters of the heating system are shown. The energy consumption curve for building heating (orange line) exhibits abrupt increases, indicating the activation of the heating system at 06:00. Following a night time pause, the system resumes operation at full capacity to counterbalance the heat loss that occurred overnight and achieve the designed room temperature. Subsequently, the heating system's performance stabilizes, operating at reduced capacity to maintain the set thermal zone temperature. The diagram of temperature profiles corresponds with the energy consumption pattern. A decline in room temperature is observed during the night when the heating system is not in function.

3.2. Statistical analysis using design of experiments

Statistical analysis is performed using Minitab software version 19, with the aim of generating regression model for prediction of building energy consumption for heating. The experimental matrix, with coded factors and the computed building energy consumption, for each simulation, is presented in Table 5. Building energy consumption for heating, is calculated using DesignBuilder for each simulation run.

Exp	**U_{wall}**	**SHGC**	**$U_{ceiling}$**	**η_H**	**$E_{H,del}$, (kWh/m^{2}ann)**
1	-1	-1	-1	-1	394,93
2	1	-1	-1	-1	226,92
3	-1	1	-1	-1	285,55
4	1	1	-1	-1	122,02
5	-1	-1	1	-1	333,79
6	1	-1	1	-1	159,19
7	-1	1	1	-1	223,32
8	1	1	1	-1	55,66
9	-1	-1	-1	1	219,40
10	1	-1	-1	1	126,06
11	-1	1	-1	1	158,65
12	1	1	-1	1	67,79
13	-1	-1	1	1	185,44
14	1	-1	1	1	88,44
15	-1	1	1	1	124,06
16	1	1	1	1	30,92

Table 5. Experimental matrix

In the DOE methodology, the statistical analysis relies on the Analysis of Variance (ANOVA), which helps to determine the significance of each factor in terms of its impact on the response variable [16]. ANOVA in this study is performed at 0,05 significance level. The preliminary analysis revealed that three and four-factor interactions are not statistically significant, therefore only main effects and effects of two-factor interactions are considered. Table 6 displays the results of ANOVA, with only statistically significant terms and their corresponding *F* and *p*-values. Based on ANOVA results, it can be concluded that all model terms are statistically significant ($p < 0{,}05$), indicating significant impact of all model terms (main effects and two-factor interaction effects) on energy consumption for heating.

Source	**DF**	**Seq SS**	**Contribution**	**Adj SS**	**Adj MS**	***F*-Value**	***p*-Value**
Model	7	155176	99.97%	155176	22168.0	4314.12	0.000
Linear	4	146488	94.38%	146488	36622.1	7127.02	0.000
$\mathrm{U_{wall}}$	1	68662	44.24%	68662	68662.3	13362.38	0.000
SHGC	1	27739	17.87%	27739	27738.9	5398.27	0.000
$\mathrm{U_{ceiling}}$	1	10025	6.46%	10025	10025.0	1950.97	0.000
η_H	1	40062	25.81%	40062	40062.0	7796.47	0.000
2-Way Interactions	3	8688	5.60%	8688	2895.9	563.58	0.000
$\mathrm{U_{wall}} \cdot \eta_\mathrm{H}$	1	5605	3.61%	5605	5604.8	1090.74	0.000
$\mathrm{SHGC} \cdot \eta_\mathrm{H}$	1	2265	1.46%	2265	2264.8	440.75	0.000
$\mathrm{U_{ceiling}} \cdot \eta_\mathrm{H}$	1	818	0.53%	818	818.2	159.24	0.000
Error	8	41	0.03%	41	5.1		
Total	15	155217	100.00%				

Table 6. ANOVA of the model for prediction of building energy consumption for heating $E_{\mathrm{H,del}}$

Figure 11 presents a Pareto chart of standardized effects, where the bar length represents the standardized effect of each model term (factors and their interactions). Statistical significance of all standardized effects is estimated at 0,05 significance level. According to standardized effects shown in Figure 11, it can be observed that wall heat transfer coefficient (U_{wall}) has the largest, while the least impact on energy consumption for heating has two-factor interaction of heat transfer coefficient of the ceiling to the unheated attic (U_{ceiling}) and heating system efficiency (η_H).

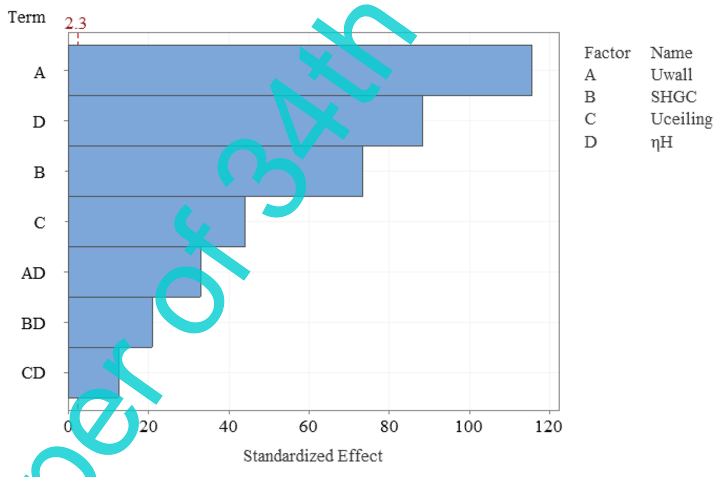
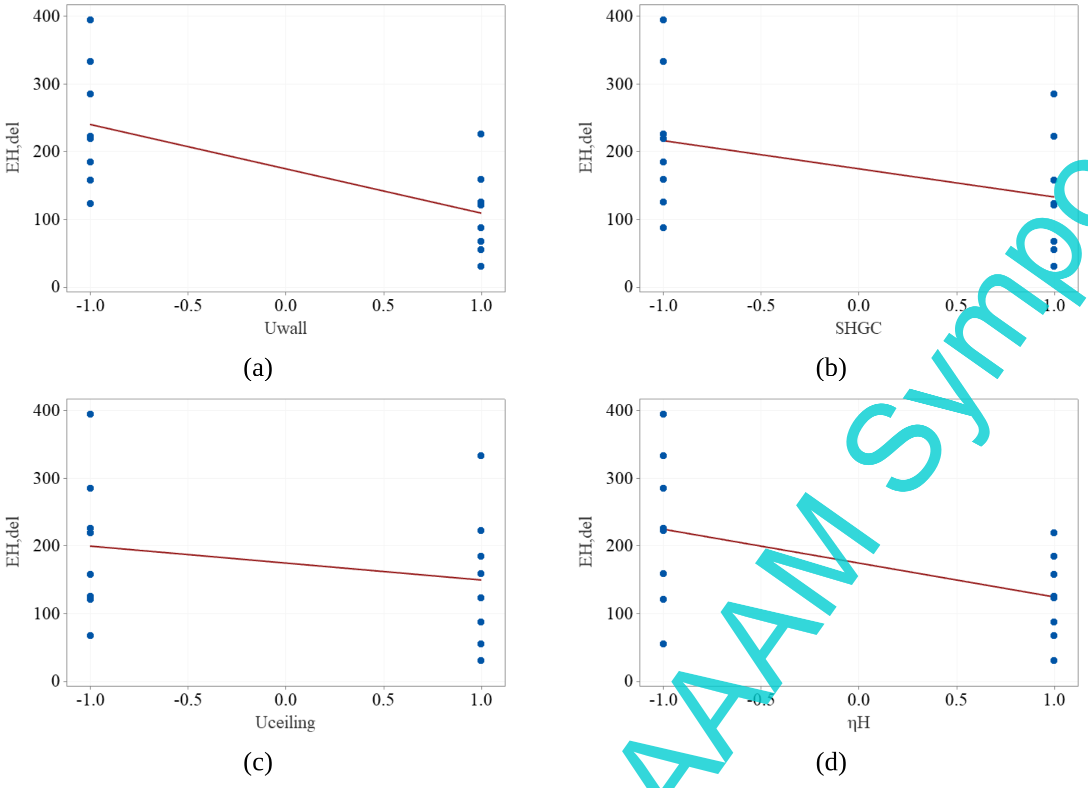


Fig. 11. Pareto chart of standardized effects

Scatter plots in Figure 12 show relationship between building energy consumption for heating, as response, and wall heat transfer coefficient ($\mathrm{U_{wall}}$), heat transfer coefficient of the ceiling to the unheated attic ($\mathrm{U_{ceiling}}$), the solar heat gain coefficient (SHGC), and the heating system efficiency (η_H), as factors, respectively. From Figure 12 it can be observed that the response linearly decreases as each factor is increased from low (-1) to high level (+1). These plots clearly show that improving the thermal characteristics of building elements (external walls, windows, ceiling towards the unheated attic and heating system) would result in a reduction of energy consumption for heating.

Using regression analysis, model for prediction of energy consumption for heating, for building located in Banja Luka, is developed and given by:

$$\begin{aligned} E_{\mathrm{H,del}} = \; & 175.134 - 65.509\, U_{\mathrm{wall}} - 41.638\, SHGC - 25.031\, U_{\mathrm{ceiling}} - 50.039\, \eta_\mathrm{H} \\ & + 18.716\, U_{\mathrm{wall}} \cdot \eta_\mathrm{H} + 11.898\, SHGC \cdot \eta_H + 7.151\, U_{\mathrm{ceiling}} \cdot \eta_\mathrm{H} \end{aligned} \qquad (1)$$



(a) (b)

(c) (d)

Fig. 12. Scatter plots of $E_{H,del}$ versus (a) U_{wall}, (b) SHGC, (c) $U_{ceiling}$, and (d) η_H

After performing ANOVA, it is necessary to validate the developed regression model using residual analysis. For the model to be considered adequate, it is necessary that residuals are normally distributed, and additionally, identically and independently distributed. To determine if the residuals follow a normal distribution, the Anderson-Darling (AD) test is performed at 0,05 significance level. If the AD test *p*-value is less than 0,05, than residuals do not follow normal distribution. Conversely, if the AD test *p*-value is greater than 0,05, than residuals follow a normal distribution. For obtained AD test statistic of 0,309 and its corresponding *p*-value of 0,522, it can be concluded that residuals are normally distributed. The normal probability plot of the residuals is displayed in Figure 13, where all data points (residuals) lie within the 95% confidence limits (outer red lines).

The second condition requires that residuals are identically and independently distributed. By examining the graphical representation of the residual's distribution around the reference line (mean of residuals), it is possible to determine whether residuals are identically and independently distributed. Figure 14 shows that residuals are randomly distributed around the reference line, indicating identical and independent distribution of residuals.

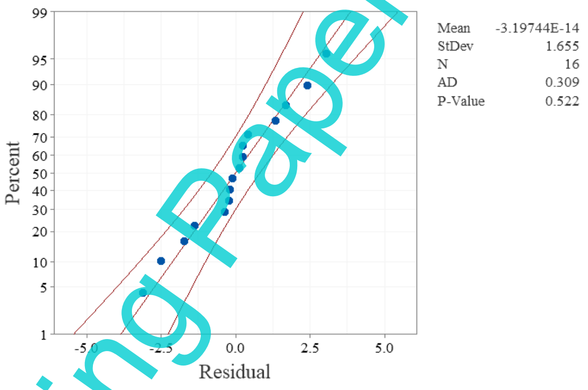


Fig. 13. Normal probability plot of residuals

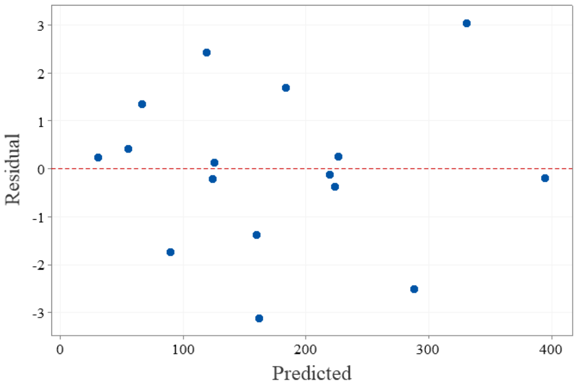


Fig. 14. Residual versus predicted values plot

Based on the model validation, it is evident that the developed model is applicable in real-world situations. This implies that the model can effectively estimate the annual energy consumption for heating of buildings in a specific category, such as SFH, constructed between 1981 and 1990.

4. Conclusion and further work

The impact of considered factors on the building energy consumption for heating is examined using statistical method, design of experiments. The research focused on single-family houses constructed between 1981 and 1990, represented via typical building from Building Typology. Selected building is located in Banja Luka in the north climate region. Dynamic simulations with very detailed input data are used to calculate building energy consumption.

The analysis resulted in a regression model that establishes the relationship between the energy consumption for heating and the considered factors. This model reveals how variations in the thermal characteristics of building elements, such as heat transfer coefficient of external walls, windows, ceilings, and heating system efficiency, affect the building's energy consumption. The most significant factor influencing the energy consumption for heating is heat transfer coefficient of the external wall, followed by the heating system efficiency.

The model is validated, confirming its applicability for predicting the energy consumption for heating of single-family houses built between 1981 and 1990 in Bosnia and Herzegovina. This research can serve as a foundation for determining potential for energy savings for both heating and cooling of residential buildings, which can be explored in future studies. Additionally, further research will focus on developing regression model for predicting annual energy consumption for cooling, particularly relevant for the southern climate region, characterized by high average daily temperatures throughout the year.

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